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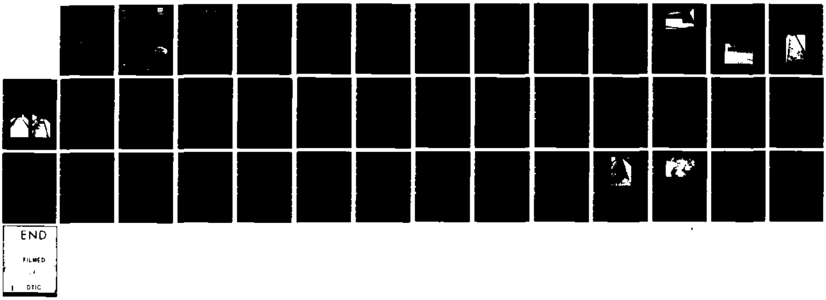

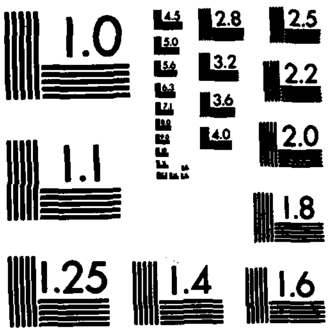

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Pilot-scale evaluation of the nutrient film technique for wastewater treatment

J.R. Bouzoun, C.J. Diener and P.L. Butler

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An experiment was conducted to determine the feasibility of using several plant species in a pilot-scale nutrient film technique (NFT) installation to further treat primary-treated effluent. The reduction of biochemical oxygen demand, total suspended solids, and nitrogen and phosphorus concentrations by the NFT is discussed. Tracer studies showed that the hydraulic retention time of the wastewater in the NFT trays was inversely related to the wastewater application rate, and that for a given flow, plants with fine root systems (such as reed canarygrass) had a much longer detention time than plants with coarse tuberous

20. Abstract (cont'd)

rhizomes (such as cattails). The BOD reduction could be described using the plug-flow reactor model with first-order kinetics.

PREFACE

This report was prepared by John R. Bouzoun, Environmental Engineer, Carl J. Diener, Civil Engineering Technician, and Patricia L. Butler, Physical Sciences Technician, of the Civil Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A161101A91D, In-House Laboratory Independent Research, Work Unit 322, Nutrient Film Technique.

T. Jenkins and S. Reed of CRREL technically reviewed the manuscript of this report. Dr. W. Jewell of Cornell University was the leader of the Cornell team with whom the authors worked to complete the project. His cooperation and leadership is gratefully acknowledged.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original.

Multiply	By	To obtain
foot	0.3048*	metre
gallon	3.785412	litre
inch	0.0254*	metre

*Exact.

PILOT-SCALE EVALUATION OF THE NUTRIENT FILM TECHNIQUE FOR WASTEWATER TREATMENT

J.R. Bouzoun, C.J. Diener and P.L. Butler

INTRODUCTION

During the 1970s the Army, like the civilian sector, had a large buildup of utilities intended to protect and improve the environment. A large number of these facilities were systems designed and constructed solely to treat the wastewater generated at Army bases. As the number of these facilities in the Army's inventory increased, so did their operating and maintenance (O&M) costs.

Fortunately wastewater treatment facilities, unlike other utilities, can produce useful byproducts that offset O&M costs. The production of methane gas during the anaerobic digestion of sewage sludge and other organic material is one example. The production of food, fiber and biomass at land treatment facilities is another.

In the past, Army wastewater treatment facilities have been designed, constructed and operated as single-objective systems whose only purpose was to treat wastewater to some prescribed level before it was discharged to a river or lake. Other than methane generation from anaerobic sludge digesters, the Army has no multiobjective wastewater treatment facilities. It would, however, reduce O&M costs if future wastewater treatment facilities were designed and operated as multiobjective systems.

There are currently two fairly well known wastewater treatment methods that can be operated as multiobjective systems. The first of these is slow-rate and overland flow land treatment, where wastewater is applied to

the land; some variety of terrestrial plant is an integral part of the treatment system. The second is aquaculture, where aquatic plants such as cattails or water hyacinths are grown in basins through which wastewater passes. In aquaculture systems the aquatic plants can be harvested and digested to produce methane gas, or they can be composted to produce a soil conditioner. A new wastewater treatment method called the nutrient film technique (NFT), which may have potential as a multiobjective system, is the subject of this report.

The nutrient film technique is a modified hydroponic plant growth technique in which a thin film of wastewater flows through the root mat of plants that grow on an impermeable and slightly inclined surface without soil. The thickness of the film, typically less than a centimeter, is the key to the NFT system. Only a portion of the roots will be immersed in the wastewater, with its available dissolved nutrients; the remainder will grow above the wastewater, where there is an abundant supply of oxygen.

It was hypothesized that the root mat of the plants would 1) filter suspended solids from the wastewater, 2) serve as a physical structure on which microorganisms, which utilize dissolved organic matter and nutrients, can attach themselves, 3) collect nutrients for use by the plants themselves. It was further hypothesized that because oxygen and nutrients are provided simultaneously to the plants, wastewater could be treated faster and in a smaller area than with slow-rate land treatment systems, which typically require several days between wastewater applications to dry and re-aerate the soil.

Initial research results indicate that a large variety of plants may be used in the NFT (Cooper 1979), making the technique feasible as a multiobjective wastewater treatment system. Aquatic plants such as cattails or bullrushes, which have very coarse root systems, can be grown in NFT trays

to treat primary wastewater. They can be harvested and then either processed to produce methane or alcohol, or composted to produce a soil conditioner. Forage grasses can be produced for animal feed, or the grass could be rolled up like sod, removed from the tray, and replanted in disturbed areas to control soil erosion. Vegetables can also be grown; this would be particularly beneficial at remote military installations where these items must be transported long distances.

This report presents the results of an NFT experiment conducted by CRREL at the Hanover, New Hampshire, wastewater treatment plant in cooperation with personnel from the Agricultural Engineering Department of Cornell University. The purposes of this experiment, which ran from March 1981 through August 1981, were to 1) determine the feasibility of using several plant species in a pilot-scale NFT system to treat primary effluent, 2) determine if a relationship exists between wastewater application rate and hydraulic retention time and if such a relationship is affected by the various root structures of different plant species, and 3) determine if the plug-flow reactor model would describe the reduction of BOD by the NFT.

MATERIALS AND METHODS

Greenhouse and NFT units

A 30- by 60-ft greenhouse with an inflated plastic roof was constructed at the Hanover wastewater treatment facility to house the NFT units (Fig. 1). In one corner of the greenhouse an area measuring approximately 15 feet square was taken up by a section of the sludge digester. This sheltered the digester from the cold and provided a storage mass for solar energy, which radiated heat back into the greenhouse at night.

Because the raw sewage coming into the treatment plant was heavily chlorinated to control odors, the effluent had a high chlorine residual and

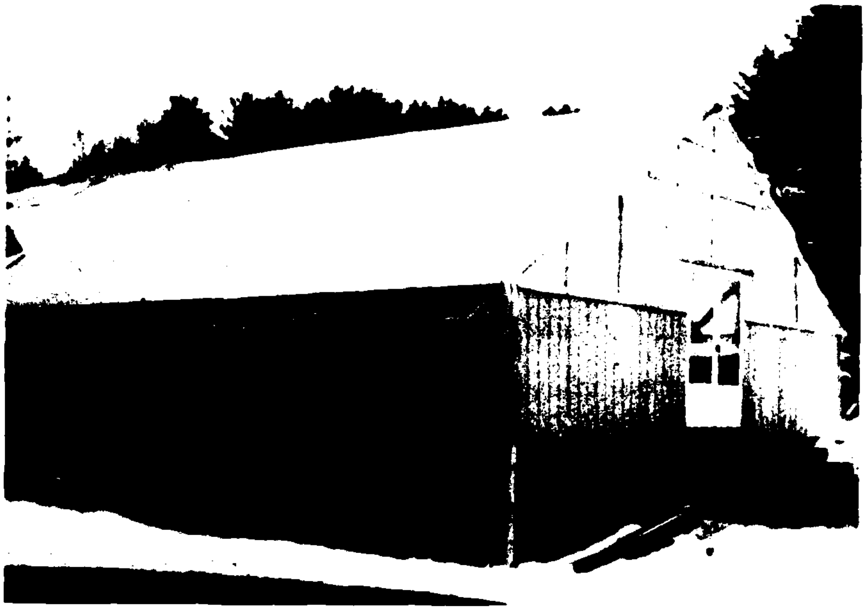
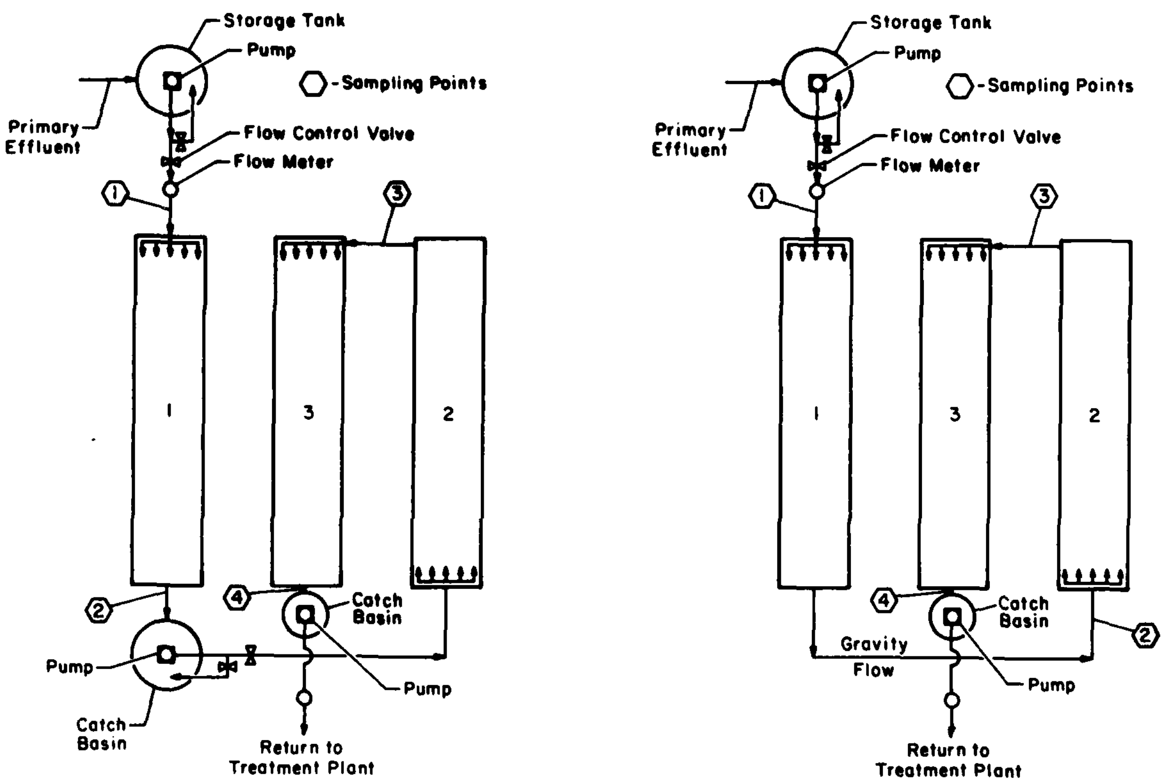


Figure 1. NFT greenhouse at the Hanover wastewater treatment plant.



a. Initial arrangement.   b. Modified arrangment.

Figure 2. Schematic of NFT installation.

could not be used for the experiment. Therefore, a tee was placed in the main influent line prior to the point where the raw sewage was chlorinated, and a portion of the raw sewage was piped into an existing pump-out chamber, which was temporarily converted to a primary clarifier. The effluent from this temporary clarifier was pumped into a 500-gallon fiberglass storage tank in the greenhouse (Fig. 2a).

Three plywood trays measuring 2.5 ft wide by 40 ft long by 0.5 ft deep were lined with plastic and placed parallel to each other in the greenhouse (Fig. 3). The first tray was placed level on concrete ˜locks on the floor of the greenhouse. Wastewater was pumped from the fibe ass storage tank through a flow meter onto one end of the first tray. ˜ then flowed across the tray into a catch basin buried in the floor of een-house. A float-actuated submersible pump pumped the wastewater out of this catch basin to the high end of the second tray, which sloped at about a 2% grade. Because the capacity of the pump was significantly higher than what was to be applied to tray 2, a fraction of the flow was returned to the

Figure 3. NFT trays prior to planting.

catch basin through a return line (Fig. 2a). The wastewater flowed down tray 2 and into a half-round section of pipe, which carried it laterally to the high end of the third tray. The third tray sloped at about a 2% grade in the opposite direction from tray 2. The wastewater then flowed down this tray and into another catch basin, where a float-actuated submersible pump pumped the effluent through a flow meter and back to the treatment plant.

In the beginning of April (after four weeks of use), tray 1 was elevated and inclined at about a 1% grade. The runoff from tray 1 then flowed laterally through a pipe to the high end of tray 2, eliminating the need to pump and recycle the effluent from tray 1 and making the wastewater flow entirely by gravity (Fig. 2b).

Figure 4. Common reed roots in tray 1 at the beginning of the experiment.

Plants

Initially (at the end of February) roots of the common reed (*Phragmites communis*) were transported from Cornell University and placed in tray 1 (Fig. 4). Juvenile cucumber plants in grow blocks were placed in tray 2 (Fig. 5), and mature reed canarygrass (*Phalaris arundinacea*) was placed in tray 3 (Fig. 6). Common reed was used in the first tray to remove the larger particles. Cucumbers were used in the second tray because it was expected that they would develop a very dense root mat and remove a considerable amount of the nitrogen and phosphorus in the wastewater. Reed canarygrass was used in the third tray to remove smaller particles. When the system was reconfigured in early April, the cucumbers were removed from tray 2 and replaced by common reed from tray 1 because the cucumbers' root systems never developed as well as expected. Cattail

Figure 5. Young cucumber plants in tray 2 at the beginning of the experiment.

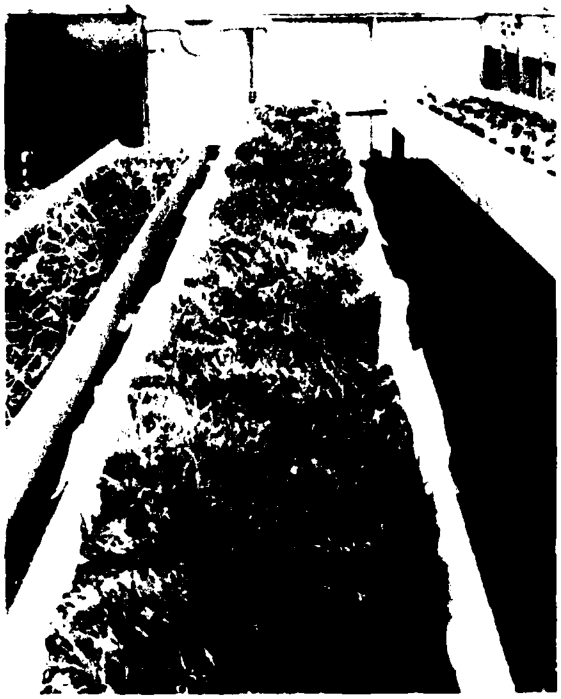


Figure 6. Reed canarygrass in tray 3 at the beginning of the experiment.

(*Typha latifolia*) roots were placed in the first 20 ft of tray 1, and bull-rush (*Scirpus lacustris*) roots were placed in the last 20 ft. Reed canary-grass was kept in the third tray throughout the experiment.

Wastewater application and sampling

During the study, several flow rates and schedules were used (Table 1). Five times during the experiment, tracer studies were conducted to determine the hydraulic retention time (HRT) of the three NFT trays. This was done by adding 900 mL of a 10,000-mg/L chloride solution to the elevated end of each tray and taking small samples of the effluent from each tray at regular time intervals. These samples were analyzed for chloride concentration. Chloride concentration was plotted as a function of elapsed time (Fig. 7), and the HRT was determined by calculating the time at which the area under the curve is equally divided (Levenspiel 1972).

Table 1. Operating schedule.

Dates	Flow Rate gal./min	Flow Rate gal./day	Schedule	Remarks
2 March-23 March	0.35	500	Continuous	Intermittent flow onto trays 2 & 3
24 March-30 March	0.70	1000	Continuous	Intermittent flow onto trays 2 & 3
31 March-16 April	-	-	-	Rearranged as described in text
17 April-8 May	2.5	750	On for 6.25 min and off for 23.75 min	
9 May-3 June	2.5	1500	On for 12.50 min and off for 17.50 min	
4 June-17 June	-	-	-	Sewage applied to trays 1 & 2 at the same rate and schedule as 9 May-3 June. Tap water applied to tray 3 to flush solids.
18 June-26 August	1.03	375	On for 30.0 min and off for 30.0 min	

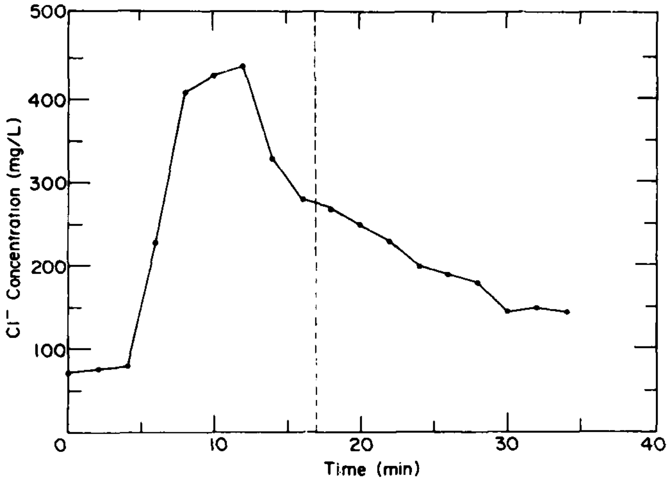


Figure 7. Chloride concentration curve used for determining the hydraulic retention time (dashed line). This curve is for the cucumbers in tray 2 on 10 March 1981.

Samples were taken at the sampling points shown in Figure 2 and analyzed for a number of volatile and nonvolatile trace organic compounds. The primary effluent being applied to the system had a high enough concentration of volatile organics, so it was not necessary to add any. The nonvolatile compounds, however, were not present in the sewage at sufficient concentrations to be studied and had to be added.

Analytical methods

Biochemical oxygen demand (BOD) was analyzed according to Standard Methods (APHA, AWWA, WPCF 1975) except that

1) Prepared reagents were purchased.

2) Samples were not seeded.

3) Dilution water was prepared by bubbling double-distilled water with filtered air (with a glass wool plug placed in the air line) through a glass diffusion tube for 2-6 hours.

For soluble BOD analysis this procedure was used on samples that had been filtered through Millipore AP40 microfiber glass filters.

Total and volatile suspended solids were analyzed according to the procedure in Millipore Bulletin AB312 (Millipore 1975) except that

1) Prepared filters were left in the drying oven at 103-105°C until needed for sample analysis. (Quality control tests indicated no change in the filter weight using this modification.)

2) Filters were weighed to the nearest 0.01 mg.

3) Pyrex filter holders were used.

4) After the sample was filtered and rinsed, it was lifted off the vacuum manifold momentarily to release a vacuum holding a film of water under the filter, then returned to its original position and allowed to dry for at least one minute. This was done so the filters would not adhere to the pan when they were dried in the oven.

Total nitrogen and phosphorus were analyzed using the persulfate digestion method (Jeffries et al. 1979, Raveh and Avnimelech 1979) and a Technicon AAll Autoanalyzer (Technicon Instrument Corporation 1977). Chloride was analyzed using an Orion Model 96-17 combination chloride electrode and an Orion Model 801 pH meter in conjunction with an Orion Model 605 electrode switch.

Volatile trace organics were analyzed by trap gas chromatography, mass spectrophotometry, and selective ion monitoring (Jenkins et al. 1981) the same day samples were collected. Less volatile trace organics were analyzed several weeks after the samples were collected by thawing the frozen samples and extracting the organics with pentane by the microextraction technique (Rhoades and Nulton 1980); they were identified using gas chromatography and electron capture detection as described in Jenkins et al. (In press).

RESULTS AND DISCUSSION

Hydraulic retention time

The results of the hydraulic retention time (HRT) studies are given in Table 2. During the first three studies the wastewater was pumped onto tray 2 and flowed by gravity onto tray 3 faster than it was pumped onto tray 1, so the catch basin at the end of tray 1 would not overflow. Also, the flow onto tray 2 was intermittent during the first three studies because the pump in the catch basin was float-actuated and cycled on and off depending on the water level in the basin. During the last two studies the system was entirely gravity flow, and the flow onto tray 1 was intermittent.

Generally the hydraulic retention times were inversely proportional to the volumetric application rates. The best example of this is for the reed canarygrass in tray 3, which was not moved or disturbed during the study. Figure 8 shows a plot of the inverse of HRT (1/T) vs application rate for tray 3. The correlation coefficient for the line of best fit is 0.88; this correlation is significant at the 5% level.

Table 2. Hydraulic retention times.

Date	Tray number and plant type	Flow rate (gal./min)	HRT (min)
10 March	1 common reed	0.34	66
	2 cucumber	0.48	17
	3 reed canarygrass	0.48	70
19 March	1 common reed	0.34	86
	2 cucumber	0.40	24
	3 reed canarygrass	0.40	104
26 March	1 common reed	0.69	87
	2 cucumber	0.74	25
	3 reed canarygrass	0.74	81
22 April	1 cattail/bullrush	2.5	24
	2 common reed	2.5	32
	3 reed canarygrass	2.5	51
6 August	1 cattail/bullrush	1.0	71
	2 common reed	1.0	83
	3 reed canarygrass	1.0	84

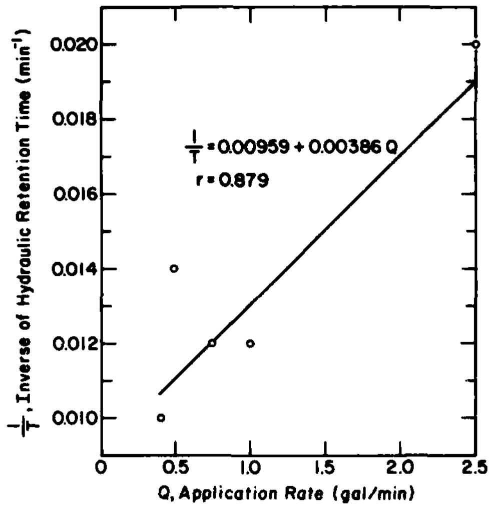


Figure 8. HRT vs application rate for reed canarygrass in tray 3.

Even though the common reed was moved from the first tray, which was level, to the second tray, which was at a 2% grade, a regression analysis of the inverse of HRT vs application rate shows a good correlation (r = 0.91) that is significant at the 5% level. With the exception of the 26 March data, the HRTs for the common reed are less than the HRTs for the reed canarygrass, even though the application rates onto the common reed were consistently less than or equal to the application rates onto the reed canarygrass. This is because the roots of the common reed are much larger and coarser than the roots of the reed canarygrass and therefore have less surface area per unit volume of tray. This means that there is less resistance to flow due to surface friction.

The cucumbers also show a high correlation (r = 0.97) between HRT and application rate. However, the HRTs of the tray with cucumbers were significantly less than for the tray with reed canarygrass. This is because the root mat of the cucumbers never filled the tray. The reed canarygrass, on the other hand, had a fully developed root system that filled the entire tray and resulted in much more surface area and therefore more surface friction.

The two HRTs for the first tray with the cattail-bullrush combination are less than the HRTs for the trays with common reed and reed canarygrass, even though the application rates were the same for all the trays. Again, this was because the individual cattail roots were much larger than the individual roots of the common reed and the reed canarygrass.

Two conclusions may be drawn from the HRT data gathered during this experiment. First, the HRT was inversely related to the volumetric flow rate onto the system. Second, the larger the individual plant roots, the shorter the HRT, because there was less resistance to water flow.

Removal of pollutants

Suspended solids. The concentrations of total and volatile suspended solids at the four sampling points shown in Figure 2 are given in Tables 3 and 4, respectively. These data are also plotted in Figures 9 and 10.

The concentrations of both total suspended solids and volatile suspended solids in the wastewater applied to the first tray were relatively low throughout the study. Also, their concentrations varied considerably, as shown by the coefficient of variation ($SD/\overline{X}$) in Tables 3 and 4. The data show that 87% of the total suspended solids applied to the first tray were volatile solids. Approximately 86% and 89% of the suspended solids applied to trays 2 and 3, respectively, were volatile solids.

The average solids concentrations in the applied wastewater and in the runoff from trays 1, 2 and 3 for the 4-20 March data show that the common reed in tray 1 and the cucumbers in tray 2 each removed approximately 45% of both total and volatile suspended solids applied to them. During the same time the reed canarygrass in tray 3 removed more than 70% of the solids applied to it. This difference is due to the different root structures of the plants. The common reed has very coarse tuberous rhizomes with a few fine root hairs. The young cucumber plants have a

Table 3. Total suspended solids concentrations (mg/L).

	Sampling point			
Date	1	2	3	4
4 March	84	31	5.6	2.4
11 March	38.4	17.2	11.4	3.3
13 March	26.3	21.8	15.6	2.6
18 March	45	27.5	19.9	5.5
20 March	34	31.9	16.2	4.3
$\bar{X}$	45.5	25.9	13.7	3.6
%ΔX		43	47	74
SD	22.5	6.3	5.5	1.3
SD/X	0.45	0.24	0.40	0.36
25 March	47	26.6	35.8	6.6
%ΔX		43	-35	82
15 April	54	25.8	18.4	20.6
22 April	40	27.3	20.3	9.4
24 April	36	23.3	17.1	5.6
29 April	65	57.8	23.8	8.4
1 May	39	27.2	14.3	8.7
6 May	39	26.9	14.3	8.3
8 May	33	23.2	16.8	5.6
$\bar{X}$	43.7	30.2	17.9	9.5
%ΔX		31	41	47
SD	11.5	12.3	3.4	5.1
SD/X	0.26	0.41	0.19	0.54
13 May	46	21.9	15.5	10.2
20 May	37.3	17.4	16.0	7.8
22 May	39	23.0	26.4	16.5
27 May	44	23.1	20.1	16.9
29 May	50	28.4	31.9	20.4
3 June	56	21.8	26.6	11.8
$\bar{X}$	45.4	22.6	22.8	13.9
%ΔX		50	-1	39
SD	7.0	3.5	6.6	4.8
SD/X	0.15	0.15	0.29	0.35
Overall				
$\bar{X}$	44.9	26.5	19.2	9.2
%ΔX		41	28	52
SD	13.1	8.5	7.1	5.6
SD/X	0.29	0.32	0.37	0.61

Table 4. Volatile suspended solids concentrations (mg/L).

	Sampling point						
Date	1		2		3		4
4 March	68		27		5		2.3
11 March	33.1		15.6		10.2		2.9
13 March	-		19.6		13.8		2.5
18 March	39		24.7		17.8		5.0
20 March	29		28.9		14.3		3.8
$\bar{X}$	42.3		23.2		12.2		3.3
%ΔX		45		47		73	
SD	17.6		5.5		4.9		1.1
SD/X	0.42		0.24		0.40		0.33
25 March	38		22.7		31.1		5.7
%ΔX		40		-37		78	
15 April	44		21.1		15.4		18.2
22 April	34		23.1		18.2		8.7
24 April	31		19.9		15.7		5.4
29 April	58		47.6		21.5		7.8
1 May	35		23.0		12.7		7.7
6 May	34		23.7		13.0		7.8
8 May	29		19.4		16.2		5.4
$\bar{X}$	37.9		25.4		16.1		8.7
%ΔX		33		37		46	
SD	10.1		9.9		3.0		4.4
SD/X	0.27		0.39		0.19		0.51
13 May	33		17.7		13.0		9.4
20 May	32.7		16.3		14.7		7.7
22 May	35		20.4		24.1		15.5
27 May	39		19.4		18.0		15.5
29 May	44		23.4		28.0		19.3
3 June	49		18.4		23.5		11.6
$\bar{X}$	38.8		19.3		20.2		13.2
%ΔX		50		-5		35	
SD	6.6		2.5		5.9		5.9
SD/X	0.17		0.13		0.29		0.45
Overall							
$\bar{X}$	39.1		22.7		17.1		8.5
%ΔX		42		25		50	
SD	10.3		6.9		6.2		5.2
SD/X	0.26		0.30		0.36		0.61

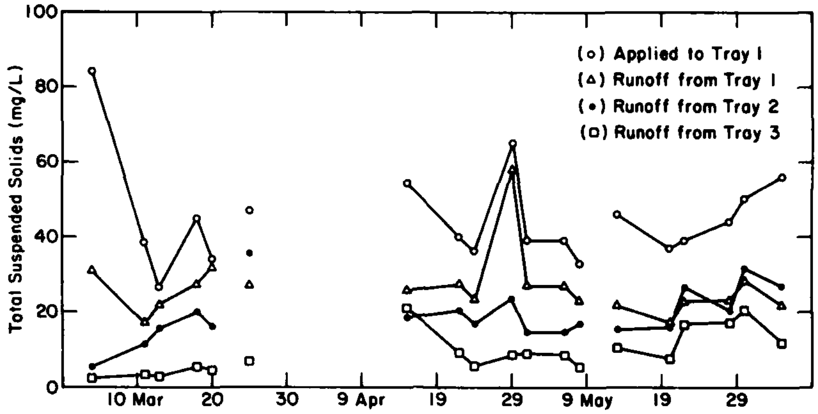


Figure 9. Total suspended solids data.

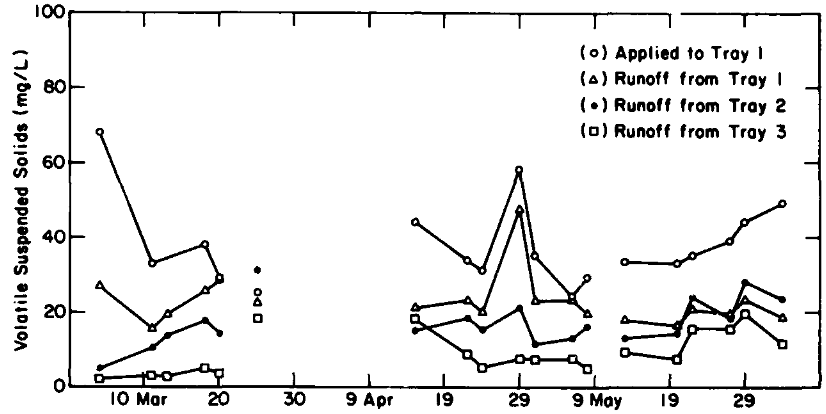


Figure 10. Volatile suspended solids data.

small root mat of very fine roots that offer little flow resistance or filtration capability. The reed canarygrass, on the other hand, had a 2- to 4-inch-thick, well-developed system of relatively fine roots that filled the tray.

The data collected on 25 March show that approximately 35% more solids ran off of the tray with the cucumbers than were applied to it. Visual observations confirmed that previously entrapped solids from the roots and solids that had settled on the bottom of the tray were being flushed out due to the increased velocity of the wastewater.

During the next sampling period (15 April through 8 May), after the system had been modified so that it was entirely gravity flow, the flow

rate onto the first tray was increased and the wastewater was applied intermittently (Table 1). The reed canarygrass removed fewer solids than in the two previous loading conditions, but it still removed more solids than the first two trays.

During the fourth sampling period (13 May through 3 June) the instantaneous flow rate was the same as in the previous sampling period (2.5 gal./min), but the amount of time the wastewater was applied to the first tray was doubled from 6.25 minutes to 12.50 minutes for each half-hour cycle. During this sampling period the cattails and bullrushes in tray 1 removed more solids than the other trays. The common reed was ineffective in removing solids during this sampling period, and the reed canarygrass removed slightly more than a third of the solids that were applied to it. The increased removal of solids by the cattails and bullrushes during this sampling period was most likely due to the large amount of root growth that took place. Based on visual observations the cattail and bullrush root mat was estimated to have more than doubled in volume from the time the rhizomes were first put in place in early April.

In general, plants with fine root systems are more effective than plants with coarse root systems in removing solids. Also, an inverse relationship exists between application rate and solids removal efficency. Simply stated, this means that the finer the root system, the better the solids removal for a specific flow rate, or for a specific root system, the lower the flow rate, the better the solids removal.

Biochemical oxygen demand. The concentrations of BOD and soluble BOD at the four sampling points are given in chronological order in Tables 5 and 6, respectively. These data are also plotted in Figures 11 and 12. The soluble fraction of the BOD in the wastewater applied to tray 1 was relatively constant throughout the study, averaging approximately 68% with

Table 5. BOD concentrations at sampling points (mg/L).

Date	Sampling point 1	2	3	4
4 March	152	74	12.3	3.7
11 March	120	78	52	11.3
13 March	108	70	56	10.7
20 March	97.5	64	37.8	17.1
$\bar{X}$	119.4	71.5	40.0	10.7
%ΔX		40	44	73
SD	23.6	6.0	19.8	5.5
SD/X	0.20	0.08	0.49	0.51
25 March	114	82	85.8	32.8
%ΔX		28	-4	62
22 April	116	98	68	39
24 April	111	63	55	32
29 April	171	133	96	45
1 May	111	83	58	32
6 May	148.5	108	81	48.4
8 May	114	97	64.5	30
$\bar{X}$	128.6	97	70.4	37.7
%ΔX		25	27	46
SD	25.2	23.5	15.5	7.7
SD/X	0.19	0.24	0.22	0.20
13 May	78	92	72	48
22 May	111	92	64	55
27 May	128	104	77.3	61.2
29 May	123	88	70	56
3 June	141	73	65	43
$\bar{X}$	116.2	89.8	69.7	52.6
%ΔX		23	22	25
SD	23.9	11.1	5.4	7.2
SD/X	0.20	0.12	0.08	0.14
Overall				
$\bar{X}$	121.5	87.4	63.4	35.3
%ΔX		28	27	44
SD	22.6	18.3	19.6	17.4
SD/X	0.19	0.21	0.31	0.49

a standard deviation of 12%. Conversely the particulate fraction of the wastewater BOD applied to tray 1 averaged 32%. The average percent soluble BOD at sampling points 2, 3 and 4 were 79, 73 and 30%, respectively, with standard deviations of 9, 11 and 13%.

Table 6. Soluble BOD concentrations at sampling points (mg/L).

	Sampling point						
Date	1		2		3		4
4 March	90		-		6.6		2.3
11 March	83		61		46		10.7
13 March	80		50		42		8.5
20 March	77.3		41.4		22.8		11.6
$\bar{X}$	82.6		50.8		29.4		8.3
%ΔX		38		42		72	
SD	5.5		9.8		18.2		4.2
SD/X	0.07		0.19		0.62		0.51
25 March	80.3		62.4		60.6		32.7
%ΔX		22		03		46	
22 April	85		74		52		20
24 April	76		63		38		26
29 April	102		92		73		37
1 May	79		64		48		27
6 May	85		88.2		45.5		42.9
8 May	92		74.4		41.5		26.7
$\bar{X}$	86.5		75.9		49.7		29.9
%ΔX		12		35		40	
SD	9.4		12.0		12.4		8.4
SD/X	0.11		0.16		0.25		0.28
13 May	75		74		62		45
22 May	71		74		56		45
27 May	75		81		61.2		46.3
29 May	84		71		56		45
3 June	65		72		44		31
$\bar{X}$	74		74.4		55.8		42.5
%ΔX		-1		25		24	
SD	6.9		3.9		7.2		6.4
SD/X	0.09		0.05		0.13		0.15
Overall							
$\bar{X}$	81.2		69.5		47.2		28.6
%ΔX		14		32		39	
SD	8.8		13.2		16.0		14.6
SD/X	0.11		0.19		0.34		0.51

The reed canarygrass removed the greatest percentage of BOD and soluble BOD during the study, even though their average concentrations in the wastewater applied to it were only 35.3 and 28.6 mg/L, respectively. The root density and root surface area appears to have been a major factor in BOD removal. As was the case with suspended solids removal, the greater

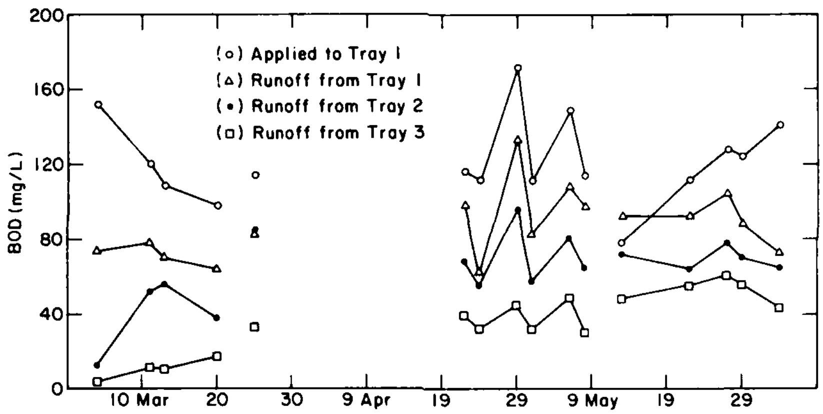


Figure 11. BOD data.

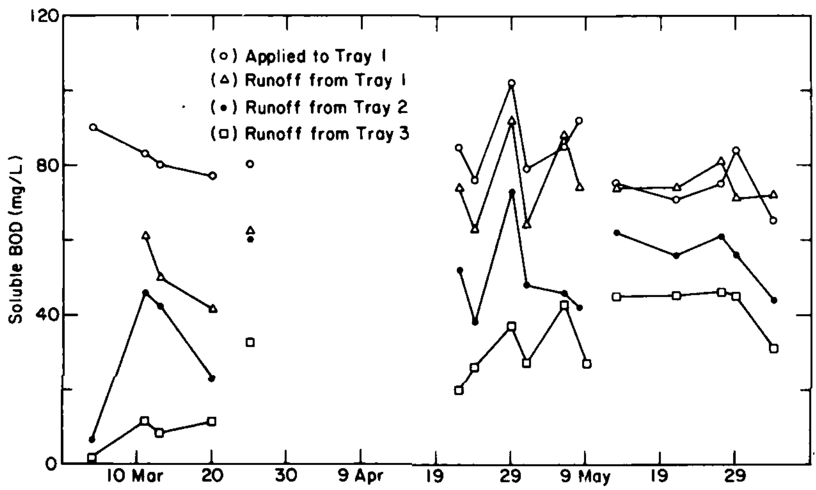


Figure 12. Soluble BOD data.

the root surface area per unit volume of tray, the greater the removal of BOD. There are two reasons for this. First, finer root systems, with greater surface areas, filter more of the particulate fraction of the BOD than coarse root systems. Second, the greater surface area of the finer root system provides more sites where microorganisms, which oxidize the soluble fraction of the BOD, may attach themselves. As a result, it may be hypothesized that there is a greater density of these microorganisms.

The kinetics of BOD removal by the NFT was examined by using the plug-flow reactor model and first-order kinetics to analyze the BOD data from the tray containing the reed canarygrass. The results are shown in

Table 7. BOD data for tray 3.

1	2	3	4	5	6	7	8
Date	Daily volume (gal.)	Flow (gal./min)	HRT (min)	C (mg/L)	C_o (mg/L)	C/C_o	Ln C/C_o
4 March	217.6	0.151	98.2	3.7	12.3	0.301	-1.201
11 March	484.0	0.336	91.8	11.3	52.0	0.217	-1.526
13 March	538.0	0.374	90.6	10.7	56.0	0.191	-1.655
20 March	570.6	0.396	89.9	17.1	37.8	0.452	-0.793
25 March	968.5	0.673	82.0	32.8	85.8	0.382	-0.962
22 April	1146.3	3.82	41.4	39.0	68.0	0.574	-0.556
24 April	1016.8	3.38	44.1	32.0	55.0	0.582	-0.542
29 April	624.7	2.08	56.7	45.0	96.0	0.469	-0.758
1 May	943.2	3.14	46.0	32.0	58.0	0.552	-0.595
6 May	690.9	2.30	54.1	48.4	81.0	0.598	-0.515
8 May	759.8	2.53	51.6	30.0	64.5	0.465	-0.765
13 May	1085.5	1.81	60.3	48.0	72.0	0.667	-0.405
22 May	1604.0	2.67	50.2	55.0	64.0	0.859	-0.152

Table 7. The flow rates given in column 3 of Table 7 were determined by dividing the volumes in column 2 by the number of minutes per day that wastewater was applied to the system. The retention times in column 4 were determined by using the equation of the line of best fit from Figure 4 ($1/HRT = 0.00959 + 0.00386\ Q$). Then a regression analysis was performed on $\ln C/C_o$ as a function of HRT, where C_o is applied BOD concentration and C is the runoff BOD concentration (Fig. 13). The equation for the line of best fit, which has a correlation coefficient of 0.80 (significant at the 1% level), is

$$\frac{C}{C_o} = 1.323\ e^{-0.016t} \quad .$$

This equation is of the general form

$$\frac{C}{C_o} = e^{-kt}$$

where

e = base of natural logarithms

k = reaction rate constant ($time^{-1}$)

t = hydraulic retention time.

This is the plug-flow reactor model with first-order kinetics (Weber 1972). The term C/C_o is the ratio of the concentration of (in this case) BOD remaining in the reactor after time t to the concentration of BOD flowing into the reactor; in other words it is the percent BOD remaining after time t. As a result of this preliminary analysis, it appears that the first-order, plug-flow reactor model will be generally applicable to describing the removal of BOD by the NFT. Developing this type of model in conjunction with a more detailed model to predict hydraulic retention time is the objective of current and future research.

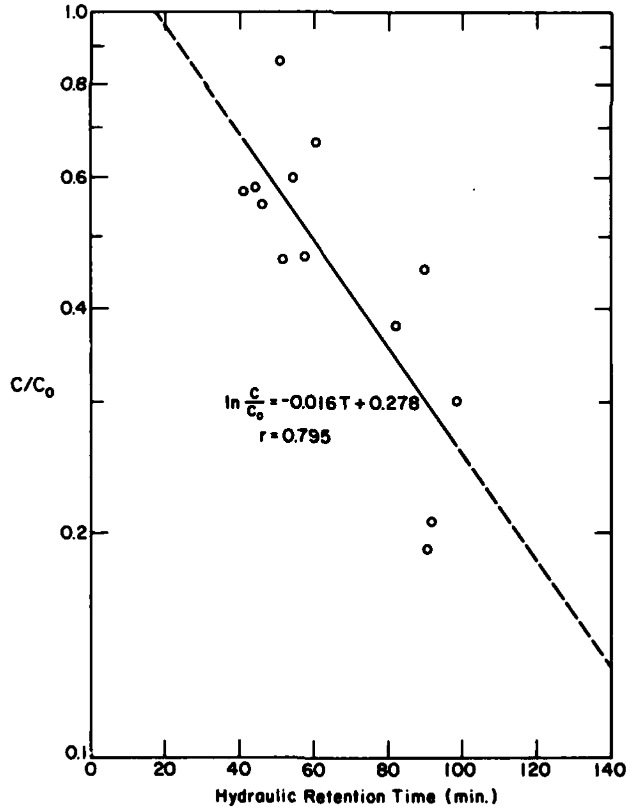


Figure 13. C/C_o vs hydraulic retention time for reed canarygrass.

Nitrogen. During the first two sampling periods, the total nitrogen concentration of the wastewater was reduced approximately 11% and 15%, respectively, by the first tray (Table 8, Fig. 14). More nitrogen was removed during the second sampling period after the flow rate was doubled, possibly because the common reed was taking up the nitrogen more rapidly due to an increase in growth rate. During the third and fourth sampling periods the total nitrogen concentration in the wastewater was reduced 6% and 4%, respectively, by the first tray. During these sampling periods the increased flow rate apparently did affect the removal of nitrogen.

The removal of nitrogen from the wastewater as it passed through tray 2 paralleled the behavior of the first tray. Despite the doubled flow rate, the removal of total nitrogen increased from an average of 8% during the first sampling period to 12% during the second sampling period. Again, this may be due to an increase in the growth rate of the cucumber plants. During the last two sampling periods the reduction in total nitrogen decreased from 10% to 5%, when the flow rate was increased through the common reed.

Nitrogen removal by the third tray with reed canarygrass was relatively high during the first two sampling periods and then fell off substantially during the third and fourth sampling period due to the increased flow rates. During the first and second sampling period the third tray removed approximately 24% and 20% of the total nitrogen applied to it. During the third and fourth sampling period nitrogen removal declined to 9% and -2%, respectively. There are two possible reasons for the better nitrogen removal by the third tray. First, reed canarygrass has a finer and denser root system than the other plants, so it filtered out more of the solids, which contained nitrogen. Second, unlike the other plants the reed canarygrass was mature and actively growing when it was placed in the

Table 8. Total nitrogen concentrations at sampling points (mg/L).

Date	Sampling point 1	2	3	4
4 March	24.5	19.3	16.0	12.5
6 March	29.3	24.0	22.3	13.3
11 March	20.3	19.5	19.3	17.0
18 March	25.0	23.0	22.5	18.1
20 March	24.0	23.0	19.8	15.5
$\bar{X}$	24.6	21.8	20.0	15.3
%ΔX		11	8	24
SD	3.2	2.2	2.6	2.4
SD/X	0.13	0.10		
25 March	24.4	20.4	19.5	14.9
27 March	21.8	19.0	15.0	12.7
$\bar{X}$	23.1	19.7	17.3	13.8
%ΔX		15	12	20
SD	1.8	1.0	3.2	1.6
SD/X	0.08	0.05		
15 April	23.7	22.0	19.5	18.0
17 April	22.3	19.5	18.5	20.3
22 April	29.6	24.9	20.3	17.1
24 April	25.9	29.2	21.5	17.6
29 April	28.1	27.0	25.0	21.7
1 May	21.7	22.4	24.1	21.7
6 May	26.5	24.8	24.3	22.3
8 May	31.5	26.0	23.3	22.3
$\bar{X}$	26.2	24.5	22.1	20.1
%ΔX		6	10	19
SD	3.5	3.1	2.4	2.2
SD/X	0.13	0.13		
13 May	24.5	23.8	22.8	21.8
15 May	16.8	15.8	14.5	14.7
20 May	19.3	17.6	16.2	16.8
22 May	21.2	20.0	18.2	18.2
27 May	21.0	20.3	20.3	20.4
29 May	23.0	22.6	21.4	21.0
3 June	22.0	21.1	21.1	21.6
$\bar{X}$	21.1	20.2	19.2	19.6
%ΔX		4	5	2
SD	2.5	2.8	3.0	2.7
SD/X	0.12	0.14		
Overall				
$\bar{X}$	23.9	22.1	20.2	18.2
%ΔX		8	9	10
SD	3.6	3.2	3.0	3.3
SD/X	0.15	0.15	0.15	0.18

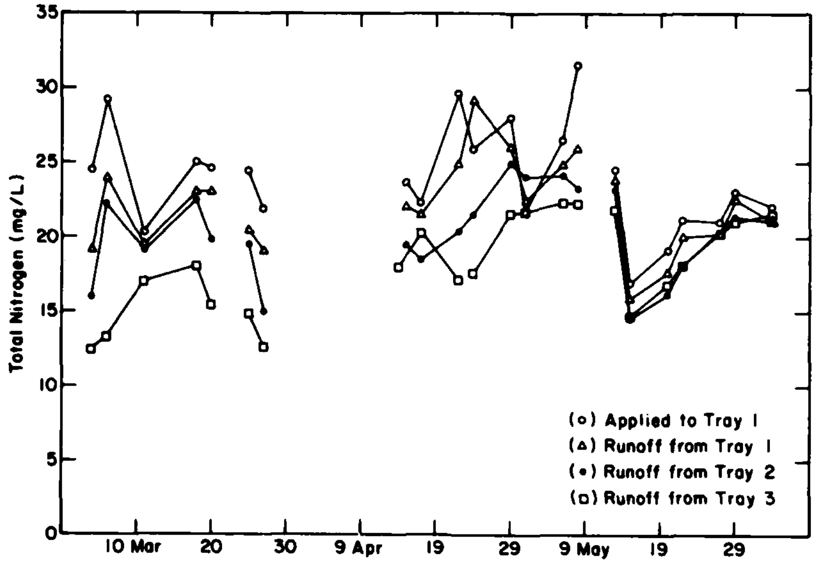


Figure 14. Total nitrogen data.

tray (Fig. 6); therefore it would have immediately begun to take up the nitrogen and other nutrients it required to sustain its growth. This accounts to a large degree for the large difference between the removal of nitrogen by trays 1 and 2 and that by tray 3 during the first two sampling periods.

Phosphorus. The removal of total phosphorus during this experiment closely paralleled the removal of total nitrogen (Table 9, Fig. 15). The -2% removal (net export) of phosphorus during the fourth sampling period was most likely due to the flushing of solids that had accumulated in the root mat. In general, as the flow rates increased, the removal of phosphorus declined. Also, the plants with the finer roots removed more phosphorus than those with coarser roots.

Trace organics. The concentrations of seven volatile organic compounds and four nonvolatile organic compounds at the four sampling points are given in Tables 10 and 11, respectively. In each instance the concentrations of volatile trace organics were reduced by 90% or more between sampling points 1 and 4. The exception was methylene chloride from the 12

Table 9. Total phosphorus concentrations at sampling points (mg/L).

Date	Sampling point 1		2		3		4
4 March	6.2		5.0		3.8		3.9
6 March	6.1		5.3		5.5		3.8
11 March	5.2		4.9		4.6		4.1
13 March	5.4		5.3		5.2		4.8
18 March	5.3		4.8		4.8		4.3
20 March	5.4		5.2		4.1		3.2
$\bar{X}$	5.6		5.1		4.7		4.0
%ΔX		9		8		15	
SD	0.4		0.2		0.7		0.5
SD/X	0.07		0.04		0.15		0.13
25 March	5.2		4.8		4.8		4.6
27 March	4.6		4.4		4.3		4.1
$\bar{X}$	4.9		4.6		4.6		4.3
%ΔX		6		0		7	
SD	0.4		0.3		0.4		0.4
SD/X	0.08		0.07		0.09		0.09
15 April	5.6		5.3		5.0		5.7
17 April	5.4		5.4		4.8		4.8
22 April	5.5		5.3		4.8		4.3
24 April	5.2		4.9		4.8		4.4
29 April	6.4		6.3		6.1		5.9
1 May	5.7		5.3		4.9		4.7
6 May	6.2		6.3		6.1		6.3
8 May	6.1		5.7		5.2		5.1
$\bar{X}$	5.8		5.6		5.2		5.1
%ΔX		3		7		2	
SD	0.4		0.5		0.6		0.7
SD/X	0.07		0.09		0.12		0.14
13 May	5.2		5.5		5.4		5.3
15 May	3.9		3.7		3.4		3.5
20 May	5.0		4.7		4.5		4.4
22 May	5.5		5.3		5.2		5.1
27 May	5.9		5.8		5.8		5.9
29 May	6.0		5.9		5.7		5.7
3 June	6.5		6.3		6.3		6.4
$\bar{X}$	5.4		5.3		5.2		5.3
%ΔX		2		2		-2	
SD	0.8		0.9		1.0		1.0
SD/X	0.15		0.17		0.19		0.19
Overall							
$\bar{X}$	5.5		5.3		5.0		4.8
%ΔX		4		6		4	
SD	0.6		0.6		0.7		0.9
SD/X	0.11		0.12		0.15		0.18

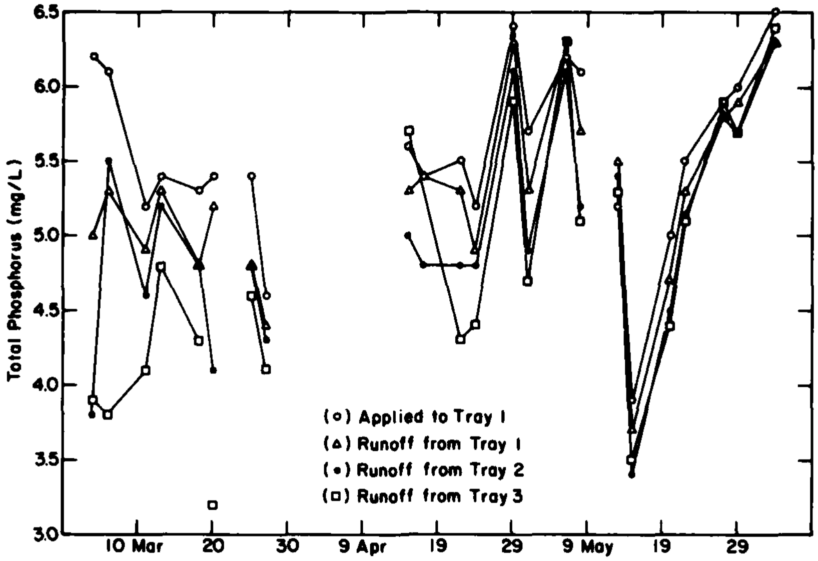


Figure 15. Total phosphorus data.

March sample. The high concentration at sampling point 1 and the subsequent increases in concentrations at points 2 and 3 were due to the cement that was used throughout the system to glue the plastic pipes together. Volatilization is thought to be the primary mechanism responsible for reducing volatile trace organics. Volatilization is enhanced with NFT because the surface area of the water is increased by the capillary action up the outside of the plant roots.

Based on concentrations the reduction of nonvolatile organics by the NFT was very good (Table 11). Sorption onto particulate matter, and the subsequent sedimentation and filtration of this particulate matter, is thought to be the primary mechanism that removes these nonvolatile trace organic compounds.

Mechanisms of pollutant removal. Although the experiment was conducted to provide an overview of the wastewater treatment capabilities of the NFT, it is possible to develop several hypotheses concerning the pollutant removal mechanisms involved in the NFT. There are two physical processes that control the removal of solids by the NFT. The first is the

Table 10. Volatile trace organics concentrations (μg/L).

Sampling point	chloroform	trichloroethylene	benzene	tetrachloroethylene	toluene	xylene	methylene chloride
12 March							
1	65.9		29.9	12.2	44.3		243
2	28.0		2.2	3.7	10.7		633
3	6.5		0.2	0.5	4.5		638
4	1.2		< 0.1	0.1	0.1		33
15 April							
1	37.2	169		9.8	19.5	29.7	
2	9.9	58.4		3.1	5.8	16.2	
3	5.1	20.5		0.9	1.4	4.8	
4	1.8	7.1		0.4	-	2.1	
24 April							
1	10.6	1.8	1.4	0.5	40.8	67.7	
2	4.9	1.0	0.4	0.3	14.2	25.2	
3	2.1	0.6	0.1	0.2	4.9	9.6	
4	1.2	0.3	< 0.1	< 0.1	1.4	2.9	

Table 11. Nonvolatile trace organics concentrations (μg/L).

Sampling point	bromoform	m-nitrotoluene	diethylphthalate	PCB 1242
		18 March		
1	47.4	58.4	82.1	39.6
2	1.87	3.41	77.6	10.0
3	0.22	0.42	43.6	6.3
4	0.23	0.17	29.6	3.9
		25 March		
1	45.8	39.2	81.8	17.6
2	3.4	5.2	64.6	4.5
3	0.59	0.26	59.7	1.7
4	0.15	BD*	19.9	1.1
		29 April		
1	44.8	10.2	100.9	21.8
2	8.2	8.0	77.2	3.0
3	5.4	3.2	76.2	2.0
4	1.4	0.50	38.6	0.45
		6 May		
1	611	228	499	738
2	122	49	239	<40
3	52	20	186	<40
4	16	29	58	<40

*BD - below detectable limits

settling or sedimentation of the solids as they flow through the tray. This process is probably the predominant one where coarse-rooted plants, such as cattails, are used. The second process is filtration of the solids by the root mat. This is probably the predominant process where plants with fine roots, such as reed canarygrass, are used, because their greater surface area provides more opportunities for physical contact between the solid particles and the roots.

The reduction of BOD by the NFT is accomplished by two processes. The first is the removal of the nonsoluble (particulate) fraction by the sedimentation and filtration of organic solids. The second is the oxidation of the soluble BOD by the microorganisms that are attached to the plant roots.

There are a number of mechanisms that may contribute to the reduction of nitrogen by the NFT. Among them are plant uptake, nitrification and denitrification, ammonia volatilization, microbial uptake, and sedimentation and filtration of insoluble nitrogen. Plant uptake, microbial uptake and the removal of the insoluble portion of the nitrogen by filtration and sedimentation are probably the predominant mechanisms. The other mechanisms are relatively sensitive to changes in pH, carbon concentration, oxygen concentration and temperature, which were not controlled in this experiment. Therefore, it is likely that these mechanisms did not significantly contribute to nitrogen removal by the NFT.

There are also several mechanisms that are responsible for the reduction of phosphorus by the NFT. They are plant uptake, microbial uptake and sedimentation and filtration of insoluble phosphorus. The NFT differs from conventional wastewater treatment facilities in that precipitation is not a factor in removing phosphorus from wastewater. It is difficult to say which of the phosphorus removal mechanisms is predominant. In an earlier study (Bouzoun and Palazzo 1982) plant uptake by reed canarygrass accounted for 41% of the phosphorus removed. The balance was removed by microbial uptake, filtration of insoluble phosphorus, or some other mechanism.

Plants

Due to limited resources, no quantitative or qualitative plant data were collected during this experiment. Therefore, the following discussion is based on visual observations and is relatively subjective.

During the first two loading periods the reed canarygrass grew vigorously and appeared to be healthy (Fig. 16). During the third and fourth loading periods the growth rate and health of the grass declined. The 2.5-gal./min flow rate caused water in the tray to be 2 or more inches

Figure 16. Healthy reed canarygrass.

deep while the wastewater was being applied. This depth could have caused the grass to be subjected to anaerobic conditions for extended periods of time, resulting in the decline in the growth rate of the grass. After the roots of the reed canarygrass were flushed with tap water (Table 1), sewage was again applied to the reed canarygrass at approximately 1 gal./min. The grass then grew vigorously for the remainder of the experiment.

The common reed grew the slowest of all the plants. It was approximately two weeks after the rhizomes were put into place before any substantial growth was noticeable. On the other hand, new growth of the cattails and bullrushes was noticeable within a few day. The bullrushes appeared to grow slightly faster than the cattails. All three aquatic

Figure 17. Mature cucumber plant.

species (common reed, cattails and bullrushes) developed into healthy stands.

The cucumbers responded to the short periods of daylight that existed when they were first put in place by flowering and fruiting almost immediately. Figure 5 shows the cucumber plants when they were first put in place; Figure 17 shows one of the plants approximately six weeks later. In that period most of the vines had grown to lengths of 2-3 feet and had several cucumbers each.

CONCLUSIONS

This experiment shows that

1) The NFT can produce useful byproducts while treating primary effluent.

2) The hydraulic retention times of the NFT units were inversely related to the volumetric application rates onto the system.

3) The finer the root system of a particular plant, the longer the hydraulic retention time.

4) The removal of BOD by the NFT depends on filtration and sedimentation of the particulate fraction of the BOD and on biological oxidation of the soluble BOD.

5) The removal of BOD by the NFT can be modeled using the plug-flow reactor model and first-order kinetics.

6) The removal of solids by the NFT depends on filtration by the plant roots and sedimentation due to the shallow depth of water.

7) The NFT is capable of significantly reducing the levels of volatile and nonvolatile trace organic compounds in primary-treated wastewater.

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